Crystal calorimeters - improving rate capabilities

Intensity Frontier prospective

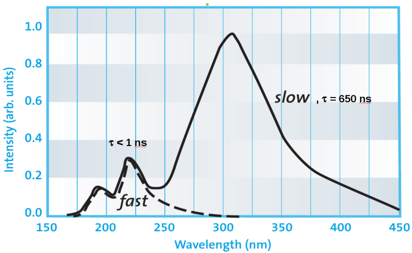
P.Murat (Fermilab)

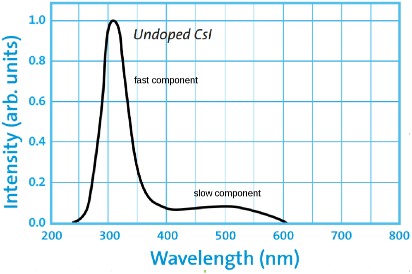
Oct 06 2015

Introduction

- crystal calorimeters win when required energy resolution $\sigma_E/\sqrt{E} < 5 - 10\%$
- at very high energies: $\sigma_E/E \;=\; a/\sqrt{E} \oplus b \oplus c/E$, energy-dependent terms small
- with the increasing beam intensity handling of the pile-up becomes increasingly important
- focus shifts towards improving resolution between two interactions - timing
- energy frontier: maintain energy resolution
- intensity frontier: preserve 1/L sensitivity scaling
- in case backround is dominated by random coincidences, single particle timing resolution also needs to improve
- **what does it take to improve the rate capabilities of the crystal calorimeters by x10?**

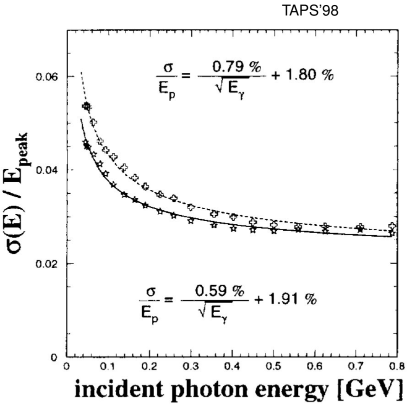
Intensity Frontier experiments: crystals

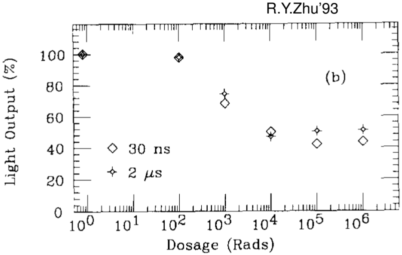




- crystal calorimeters of the current and coming intensity frontier experiments: KOTO(undoped CsI), Mu2E ($\mathrm{BaF_2}$), COMET (LYSO), g-2(PbF2)
- fast scintillators, emission time $\tau < 50$ ns
- $\mathrm{BaF_2}$, CsI emit in UV region; Cherenkov emission - $dN/d\lambda \sim 1/\lambda^2$ - also UV
- readout requires UV-sensitive photodetectors
- $\mathrm{BaF_2}$has unique rate capabilities : $\tau_{fast} < 1$ ns, 1800 photons / MeV
  - however, intensity of the slow emission component > 80% of the total
  - at high rates, the slow component needs to be suppressed

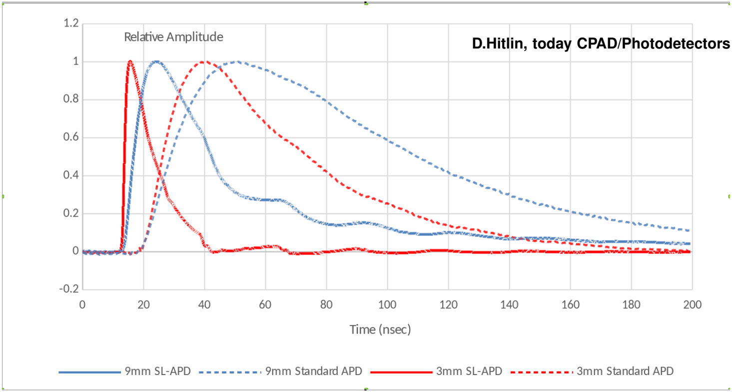
more on BaF_2crystals





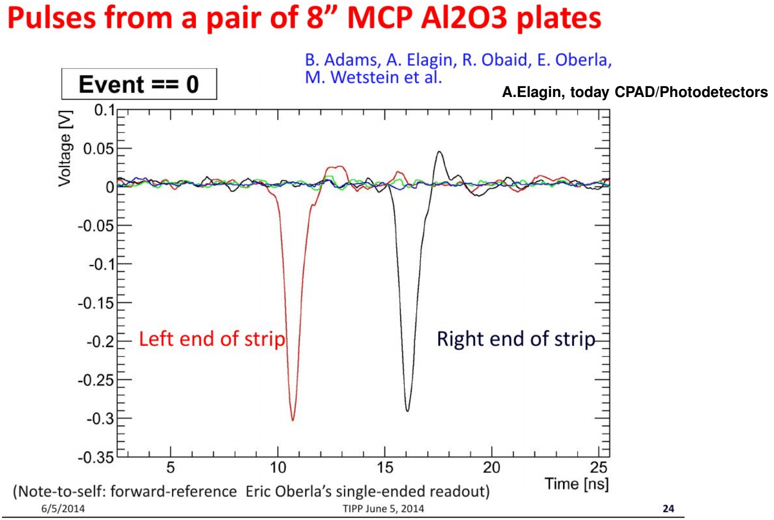
- energy resolution 2.5% at 1 GeV demonstrated (TAPS)
- light yield stable after 10 Krad

Photodetectors for BaF_2 calorimeter



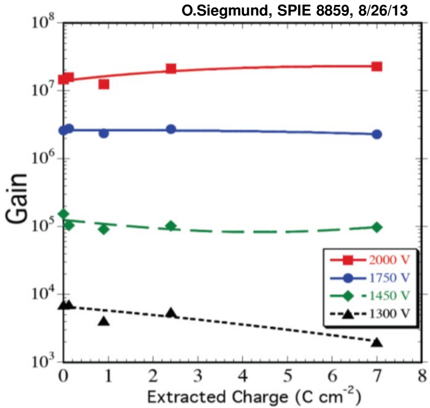
- Mu2e is planning to read out BaF_2 with large area (9x9 mm^2) UV-sensitive APDs
- these APD's also have an optical band filter - solar blind
- the signal integration time - 50-100 ns
- 1 ns fast scintllator calls for a photodetector with the response time of the order of 1 ns

A photodetector with 1 ns pulse - MCP's



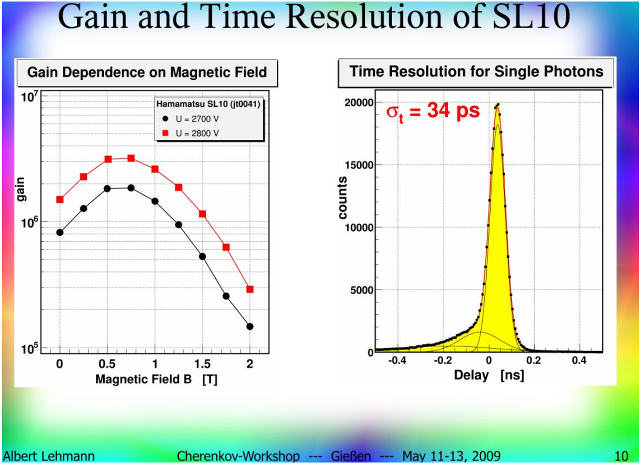
- microchannel plate-based detectors: full pulse within three nanoseconds

LAPPD MCP's lifetime measurements



- LAPPD MCP: reqular borosilicate glass , activated by atomic layer deposition (ALD)
- emission-active layer: Al_2O_3 or MgO, gain - up to (2-3)10^7 with MgO
- remarkably, no signs of gain reduction up to 7 C/cm^2 for V > 1.5 kV
- no pre-amplification needed

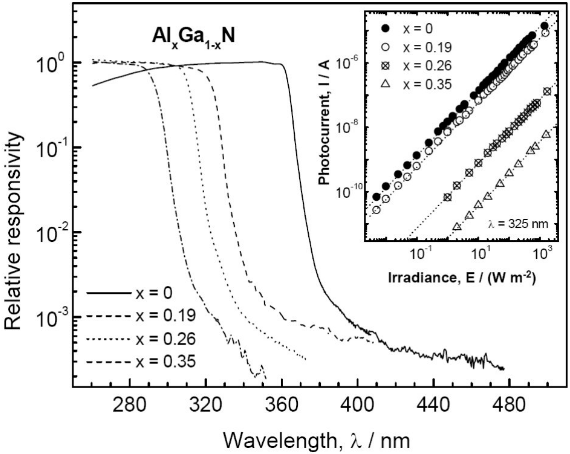
MCP's in the magnetic field



- photodetectors have to operate in the magnetic field
- PANDA RICH studies: Hamamatsu SL10 **gain at B=1.5T is** $\sim$ **60% from the gain at B=0**

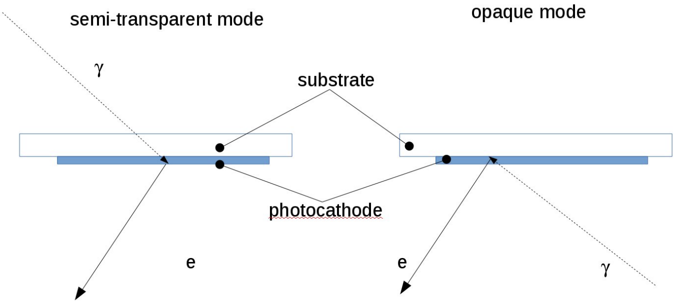
non-alcali UV-sensitive photocatodes

U.Schühle, J.-F.Hochedez, "Solar-Blind UV detectors", in ISSI Scientific Report SR-009, ISBN: 978-92-9221-938-3



- wide band semiconductors: UV sensitive and solar-blind simultaneously
- GaN (band gap = 3.5 eV) used in astrophysics for quite some time
- wide-band semiconductors are radiation hard, many GaN devices intended for use in radiation-harsh environment

Opaque vs semi-transparent photocatodes



- can deposit GaN directly on MCP - opaque mode photocathode
- crystalline GaN (MBE at $\sim$ 700 C) requires sapphire substrates
- amorphous photocatodes can be deposited at much lower temperature

GaN photocatodes: QE

O.Siegmund et al, Proc. SPIE 7021, 70211B, 2008, doi:10.1117/12.790076

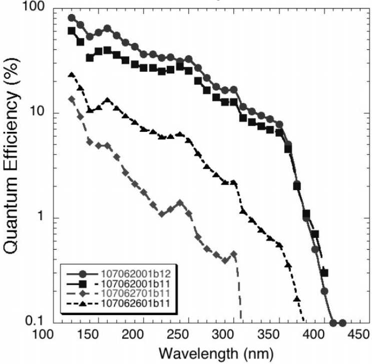


Figure 9. Opaque QE vs. wavelength for 500nm GaN on Alumina substrates (107062701 solid alumina substrate, 107062601 – substrate with 25µm holes) compared with 150nm GaN (107062001 [two thermal procedures]).

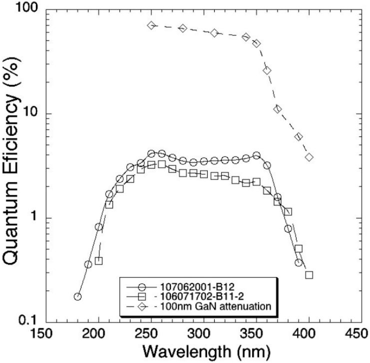
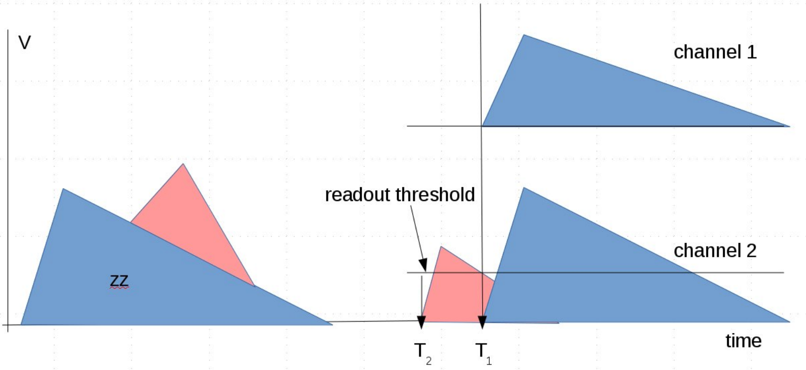


Figure 10. QDE vs. wavelength for semitransparent GaN. 150nm GaN (107062001), 100nm GaN (106071702), both on sapphire, 30nm AlGaN, P doped up to 2 x 10^{19} cm^{-3}.

- $QE_{opaque} \sim 30$ % at 220 nm
- transparent mode: lower QE overall, depends on the photocathode thickness

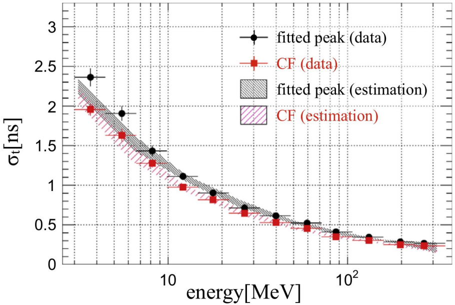
Readout: Pileup separation

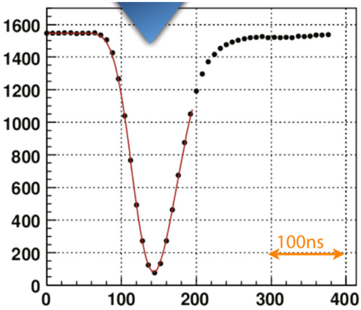


- pileup in the calorimeters usually results in “extra energy”
- it also can result in the losses
- move towards readout base on waveform sampling, pulse shape analysis

Digitizing 5 ns long pulses: data volumes

KOTO CsI, Nucl.Instrum.Meth. A786 (2015) 135-141



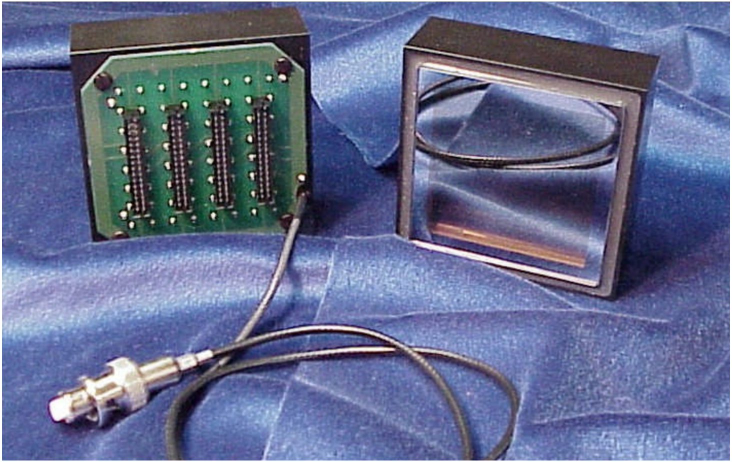


$\sim$ 200 ns range sampled at 125 MGz

- waveform digitization: timing resolution @100 MeV : $\sim$ (time bin) / 15-20
- leading edge of 1 ns : need sampling rate $\sim$ 3 GHz or above
- for comparison, Mu2e calorimeter plans to use 200 MHz sampling rate
- with pulses shorter than 5 ns, can digitize a range of 10 ns instead of 100 ns per pulse
- data volume increases with occupancy, not with the sampling rate

Photodetector packaging

PLANACON 85011-501



- can match the photodetector size to the crystal size - light yield improvement
- SiPM/APD-based readout of g-2, Mu2e: '$S_{\text{photodetector}}/S_{\text{crystal}} \sim 20\%$
- MCP-based photodetector can be made $\sim$ 1" thin

there are open questions - always

- radiation hardness: individual components don't have much to suffer from radiation
- performance: what happens when a shower tail reaches the photodetector?
- relatively new device - any long term effects ?
- LAPPD project made a low cost promise - how low $/channel could be for 1000 channels ?

Summary

- radiation-hard BaF_2 crystals provide an excellent choice for the next generation high-rate crystal calorimeters - Mu2e is exploring this option
- MCP-based photodetectors with GaN photocathodes seem to be a natural match to the BaF_2 scintillator
- combination could lead to improving the rate capabilities of intensity frontier crystal calorimeters by an order of magnitude w/o sacrificing the energy and timing resolutions